INTEGRATION OF A SELF-CONTAINED COMPACT SEED SOURCE AND TRIGGER SET FOR FLUX COMPRESSION GENERATORS

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Abstract

Two integral components that accompany an FCG in an explosively driven system is the prime power source and the trigger set. The objective of the prime power source or seed source is to provide the initial seed current/energy into the primary stage of an FCG. Another integral component in an FCG based pulsed power system is the trigger set. The trigger set is used to detonate an exploding bridge wire (EBW) which triggers the high explosives (HE's) in an FCG. This paper will discuss a recent design of a stand-alone apparatus that implements a self-contained (battery powered with full charge time less than 40 sec) [1], single–use Compact Seed Source (CSS) using solid state components for the switching scheme along with a single-use Compact Trigger Set (CTS) that also implements a similar switching technique. The CSS and CTS stand-alone apparatus developed is a system (0.005-m^3 volume and weighing 3.9 kg) capable of delivering over 360-J (~12 kA) into a 5.20-µH FCG load and approximately 2-mJ (~600 A) into the EBW. Both the CSS and CTS have trigger energies of micro-Joules at the TTL triggering level.

I. INTRODUCTION

An important aspect of the design criteria for both, the CSS and the CTS, is volume size and portability. The stand-alone apparatus implements many off-the-shelf components and utilizes minimal components to make a cost effective solution for a single shot system. This includes using bipolar junction transistors (BJT's) as the primary switching mechanism for both the CSS and the CTS. The switching scheme presented here uses a low current, high voltage N-P-N BJT, typically used in cathode ray televisions applications. Due to the low current ratings (mill-Ampere) of these transistors, they tend to only operate for a single shot before they are destroyed in this high current (hundred's to kilo-Ampere range) application. Many advantages have risen from using these BJT's that include low cost, small size, and most importantly is the triggering technique. Triggering these BJT switches requires only TTL voltage pulses often measured to have energies in the mirco-joule range [1].

A detailed evaluation will be presented about the stand-alone apparatus that contains both, the CSS and the CTS. This will discuss the individual design of each sub-system, comparing their similarities and difference in operation, along with an overview of their respective loads that include dummy resistive and inductive loads along with live EBW and HFCG loads.

Figure 1. CSS and CTS stand-alone apparatus as used in laboratory testing with fiber-optic transmitter.

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14. ABSTRACT
Two integral components that accompany an FCG in an explosively driven system is the prime power source and the trigger set. The objective of the prime power source or seed source is to provide the initial seed current/energy into the primary stage of an FCG. Another integral component in an FCG based pulsed power system is the trigger set. The trigger set is used to detonate an exploding bridge wire (EBW) which triggers the high explosives (HEs) in an FCG. This paper will discuss a recent design of a stand-alone apparatus that implements a self-contained (battery powered with full charge time less than 40 sec) [1], singleuse Compact Seed Source (CSS) using solid state components for the switching scheme along with a single-use Compact Trigger Set (CTS) that also implements a similar switching technique. The CSS and CTS stand-alone apparatus developed is a system (0.005-m3 volume and weighing 3.9 kg) capable of delivering over 360-J (~12 kA) into a 5.20-ìH FCG load and approximately 2-mJ (~600 A) into the EBW. Both the CSS and CTS have trigger energies of micro-Joules at the TTL triggering level.

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II.EXPERIMENTAL SETUP

The stand-alone apparatus houses both the CSS and CTS subsystems. It measures 15.2 cm (6 inch) in outer diameter, less than 30.5 cm (12 inch) in height, and weighs less than 4 kg (9 pounds) with a total volume of 5.56×10^3 cm^3 (0.005 m^3), as seen in Fig. 1.

The system topology is of two separate subsystems that are integrated as one, though still maintain separate power sources and trigger signals for operation. It is important to note that the CSS and CTS are self-contained systems and require no external power supplies.

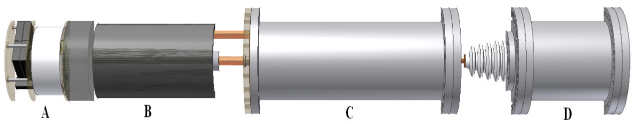

Figure 2. Three dimensional rendering of complete HFCG system. A) CSS/CTS Apparatus B) HFCG C) Power Conditioning System D) Vircator. Complete system has approximate length of 1.5 meters and is 15 cm in diameter [3].

For a complete HFCG shot test, the stand-alone apparatus is placed outside an explosive chamber that contains the HFCG. Also placed outside the explosive chamber is the load for the generator. In this particular setup, the output of the generator is connected to a power conditioning system and a Vircator as the load [2]. Though laboratory testing requires an explosive chamber to contain the HFCG, the final design of the complete HFCG system is to be housed and fired together as a single unit as pictured in Fig. 2.

Operation of the system starts as the capacitor of the CSS is charged (controlled remotely) to the desired voltage. The time to reach the desired charge voltage on the CSS capacitor can range from 30 to 40 seconds. Upon charging the CSS, the CTS is then fully charged (also controlled remotely) to approximately 1 kV, which has a charge time of hundreds of milli-seconds. Once the CTS is charged, the complete HFCG system shot is ready to be triggered.

The first component triggered is the CSS subsystem by a single TTL pulse via fiber-optic cable remotely controlled by the user. The trigger pulse turns on the solid-state switch, thus leading to the stored energy of the CSS capacitor to be dumped into the inductive load of the HFCG. This establishes the initial magnetic field, or magnetic flux, between the stator and armature of the generator. It is ideal to have the HFCG crowbar at the peak of the current magnitude supplied by the seed source. This has been approached by two different techniques in laboratory testing.

The first technique is using an electrical delay between the time of triggering the CSS and the CTS. The CTS is triggered approximately 10 to 15 μs after the CSS by another single TTL pulse via another fiber-optic cable. This in turn detonates the EBW connected to the high-explosives inside of the aluminum armature. It is important to note that another delay will proceed upon the time of detonating the EBW and the time that crowbar will take place at the generator. This additional delay is due to the mechanical (propagation) time that it takes for the expanding armature to make an electrical connection with the copper crowbar placed at the beginning of the stator. As the armature and crowbar are coupled, the seed source circuit is disconnected from the HFCG and the flux compression process of the generator begins [4].

The second technique is using an explosive delay between the time the CSS is triggered and the time crowbar takes place at the generator. This design allows the CSS and CTS to be triggered at the same time with no electrical delay. The difference in this approach is to add an explosive line delay between the EBW and the aluminum armature of the HFCG, similar to that used in previous experimentations [5]. Using the propagation velocity of the high explosives (8,092 m/s or 0.319 inch/μs), it was determined that a 4 inch length cylindrical polyvinyl tube (0.5 inch outer diameter and 0.3 inch inner diameter) stuffed with high explosives is sufficient to provide approximately 12 μs of delay from the time the CTS is triggered to the time the explosives in the armature start to detonate.

A. Compact Seed Source (CSS)

The CSS has been simplified to minimize the amount of components used in its design along with minimizing its overall volume. A CSS circuit schematic can be seen in Fig. 3.

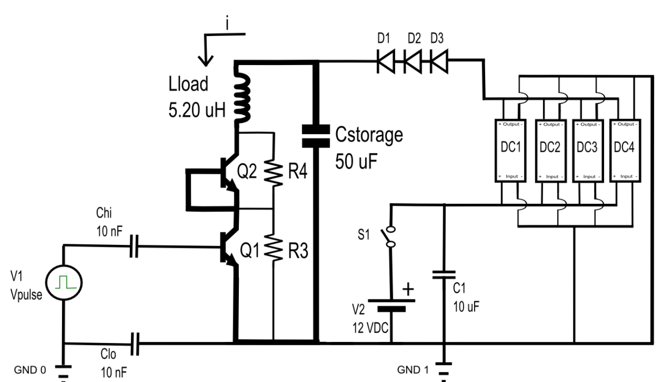

Figure 3. CSS Circuit Schematic. High current path is indicated in bold [1].

The CSS charging process is remotely controlled by a switch (S1 in Fig. 3) that connects the 12 V battery to the 4 EMCO DC to high voltage converters (DC1-DC4 in Fig. 3) rated for 5 kV maximum output. Upon closing the switch, the high voltage converters will charge the single 50 μF capacitor (Cstorage in Fig. 3) in-between 3.5 kV to 4.5 kV in approximately 30 to 40 seconds. This is

dependent on the seed energy level desired to have into the primary stage of that particular generator, though it's important to note that the seed source is capable of an energy output of over 360 J (~12 kA into a 5.20 µH inductive load) [1].

The solid-state switch is capacitively isolated (Chi and Clo in Fig. 3) from the fiber-optic receiver board. This fiber-optic receiver board accepts the TTL pulse from the remote location of the user via fiber-optic cable and doubles the voltage magnitude of the pulse to turn on Q1.

The BJT's implemented in the CSS have a collector current rating of 30 mA and a base to collector voltage rating of 2 kV by the manufacturer (base to collector voltage was measured to be 2.75 kV in lab testing). This indeed causes the transistors to be destroyed during every shot, but not before successfully switching the stored energy of the capacitor into the load. This occurrence leads to an interruption in the seed circuit current, thus causing an inductive voltage spike that measures higher than the initial charging voltage across the switch. This large voltage spike leads to a discharge arc formation between the external leads (collector and emitter) of the BJT's which re-establishes a path for current flow (similar to a spark gap).

As reported in [1], the transfer energy efficiency of the switch was still a reasonable 70% from the capacitor to the load when this arc formation occurred. Ongoing research has further improved the performance and the transfer energy efficiency of the sold-state switch. This is due to the redesign of the printed circuit board for the CSS. The transistor leads, along with the board traces were minimized to reduce parasitic inductance and resistance. A key design improvement in the switching circuit was the addition of a single gas/plasma surge arrestor tube from EPCOS, placed across the transistors. The gas tubes used in these tests were rated for 4.5 kV and 5 kV (depending on the seed energy required for the generator), and a discharge current rating of 2.5 kA.

During operation, as the transistors are switched on, they operate normally for 200 ns before the interruption of seed current flow. Instead of creating a large discharge arc external to the switches, the large inductive kick alternately breaks down the gas tube and closes it, thus providing a less resistant path for current flow. This in turn has resulted into an energy transfer efficiency increase to a value of 82%. It is important to note, that similar to most of the components used in this setup; the gas surge arrestor is only good for a single shot application due to the large magnitude of current being switched into the load.

B. Compact Trigger Set (CTS)

The CTS has a very similar design to that of the CSS with the exception of the load (it being a resistive EBW for the CTS instead of an HFCG for the CSS). The CTS is comprised of a single 9 V battery, one EMCO DC to high voltage converter, a single snubber capacitor, and a single printed circuit board the houses the fiber-optic receiver circuit and the solid-state switching circuit.

Similar to the operation procedure of the CSS, the CTS charging process is controlled remotely but instead of a user enabled switch, the user instead retains the 9 V battery. Charging the detonator is the final step taken in the overall HFCG system testing, due to precautionary safety measures. Upon connecting the 9 V battery remotely, the EMCO DC to high voltage converter, rated for 1kV output, charges the 1 µF capacitor in a few hundred milli-seconds. Upon a final check of all the components and subsystem of the HFCG, the CTS is triggered via a TTL pulse applied to the base of the single N-P-N BJT.

Unlike the CSS, the CTS utilizes only a single BJT to switch the stored energy of the 1 µF capacitor into the resistive load (EBW). This is due to a lower switching voltage level needed to detonate the EBW. The BJT used is also a different model than that used in the CSS. The CTS BJT is rated for a base to collector voltage of 1600 V and a collector current of 4 A by the manufacturer.

The RP501 EBW used in lab testing requires a threshold burst current of at least 180 amps with a fast rise-time to detonate. This became an important parameter for the design of the CTS and for choosing the capacitor to use for it. The capacitors tested in the lab are able to provide a sufficient current trigger level but it was decided to double the required minimum current level of the EBW to ensure detonation for every shot. It was decided to use the ASC 0405 x329s – 1 µF capacitor rated for 1200 VDC, operated at 1 kV charging. This was chosen primary for the more than sufficient power ratings along with a smaller package type. It is important to note that the load for the lab tests was a 0.5 Ω resistor.

III.EXPERIMENTAL RESULT

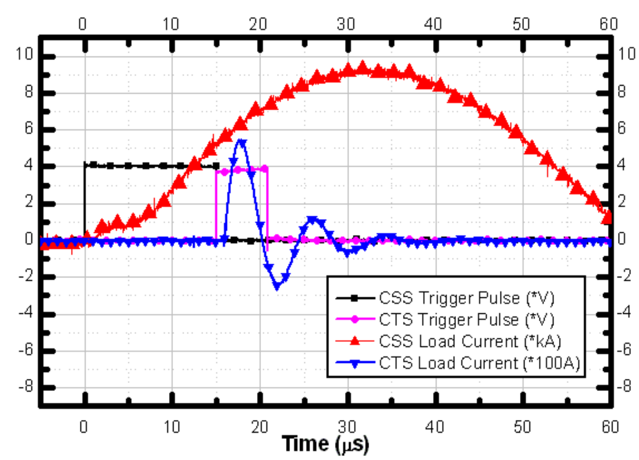

Figure 4. CSS and CTS waveforms in their respective dummy loads with an electronic trigger delay of 15 µs.

As mentioned previously, the CSS and the CTS were thoroughly tested into dummy loads before live testing with the complete HFCG system. The CSS dummy load is a 5.20 μH (20 mΩ) Litz wire inductor that mocked the primary coil of an HFCG. The CTS dummy load is a 0.5 Ω resistive load that mocked the low resistance of an EBW. Fig. 4 displays the waveforms acquired from testing of the stand-alone apparatus as it is fired into the respective dummy load of each subsystem with an electronic trigger delay of 15 μs from the time the CSS is triggered to the time the CTS is triggered. It should be noted that variation of the trigger pulses will occur due to the various triggering equipment used throughout the testing process, though the TTL magnitude levels did not change as frequently. During an HFCG system shot with an electronic trigger delay between the CSS and CTS, the HFCG armature and crowbar are coupled at an approximate time of 9 μs, which results to a seed energy of 221 J into the primary stage of the generator.

IV.CONCLUSION

The implementation of off-the-shelf components and the utilization of small package BJT's for the switches have contributed significantly to the compact size and the cost effectiveness of the stand-alone apparatus of the CSS and the CTS. The apparatus as a whole has a stored energy density of 1.92 J/inch^3 (120 mJ / cm^3) and a deliverable energy density of 1.1 J / inch^3 (60 mJ/cm$^{3)}$.

The CSS is capable of delivering seed energies of over 360 J into the primary stage winding of a flux compression generator by simply using two high-voltage N-P-N BJT's and a gas tube surge arrestor as the switching mechanism. This has proved to be a comparable switching technique to many larger and more complicated systems that may use, but not limited to, spark gaps with over voltage triggering devices. The CTS has also been illustrated to successfully provide the needed current to trigger an RP501 EBW, thus detonating the high explosives contained in an HFCG.

The design presented integrates two separate subsystems that work in sequence to successfully seed a helical flux compression with a large current pulse in the kilo-Ampere range as well as detonate the high explosives packed inside of the generator. This system has been tested in the lab and field with notable results yet leaves room for further improvement. Future work will focus on implementing a single rapid capacitor charger with two secondary transformer outputs to charge both the CSS and CTS in a few hundred milli-seconds. Focus will also be placed on optimum system shielding from a high EMI noise environment.

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